

Characterization and 3-D Modeling of Devonian Pinnacle Reefs for CO₂ Storage and Enhanced Oil Recovery

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Energy & Environmental Research Center (EERC)

Presentation Outline

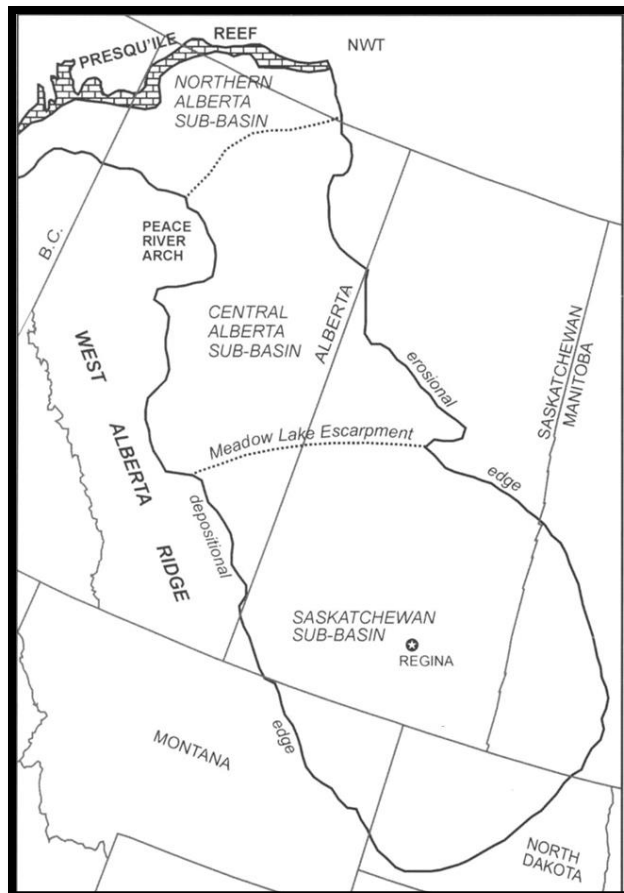
- Introduction
 - Plains CO₂ Reduction (PCOR) Partnership
 - Devonian Pinnacle Reef Overview
- 3-D Modeling
- Dynamic Simulation
- Results and Discussion
- Conclusion



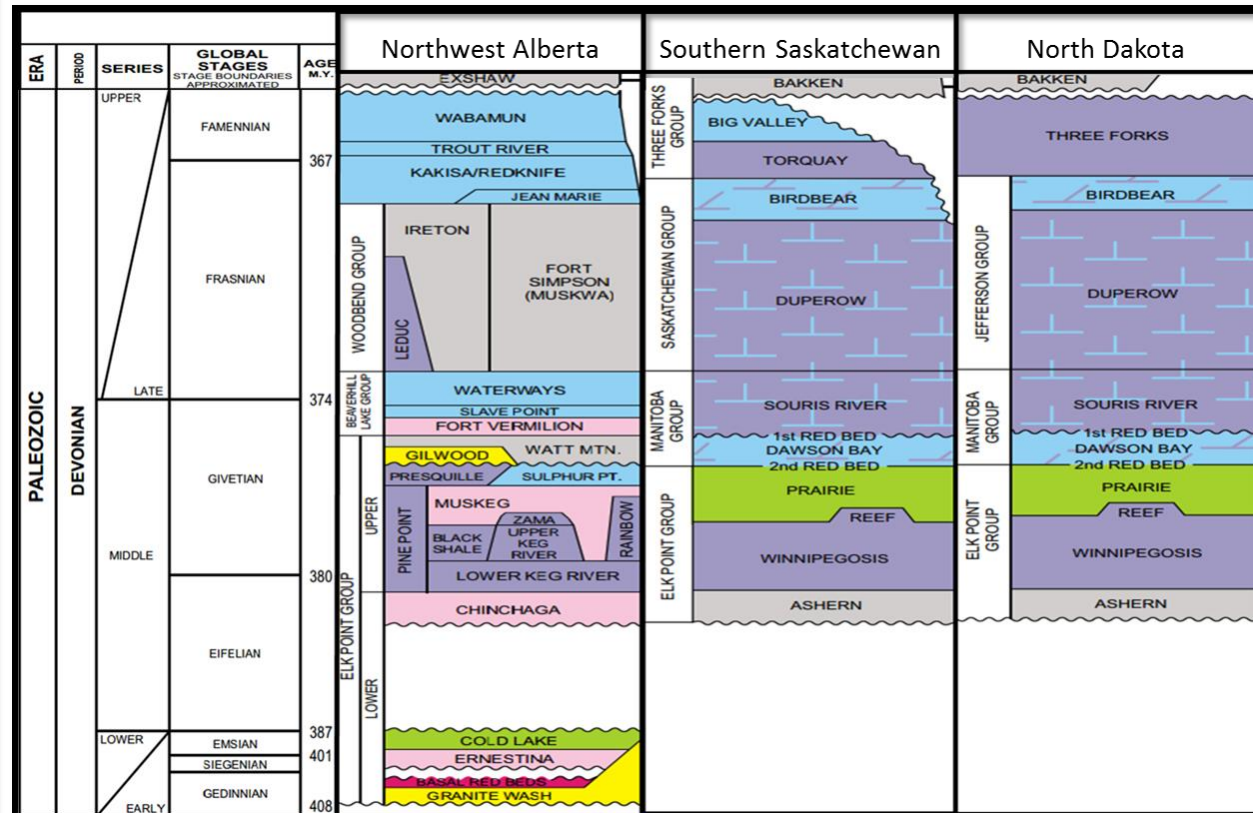
PCOR Partnership

PCOR Partnership 2003 – Present															
															
															
															
															
															
															
															

Introduction

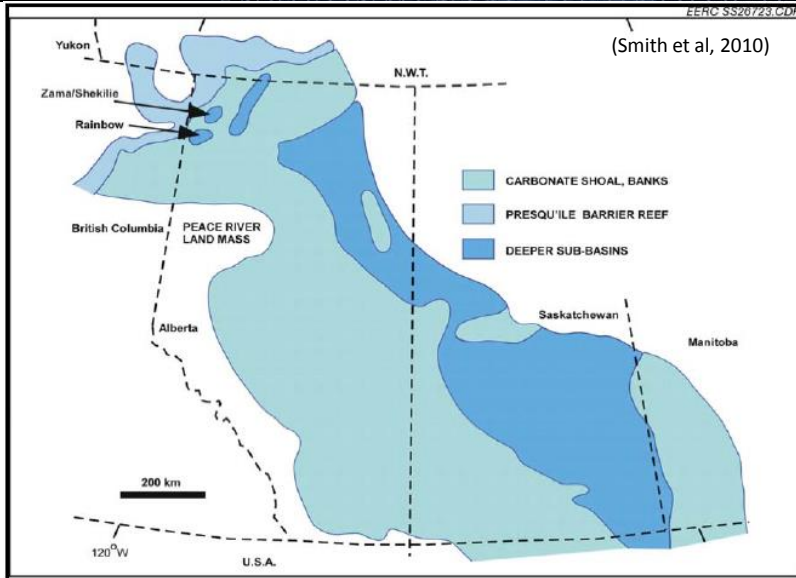


(Modified from Jin and Bergman, 2001)



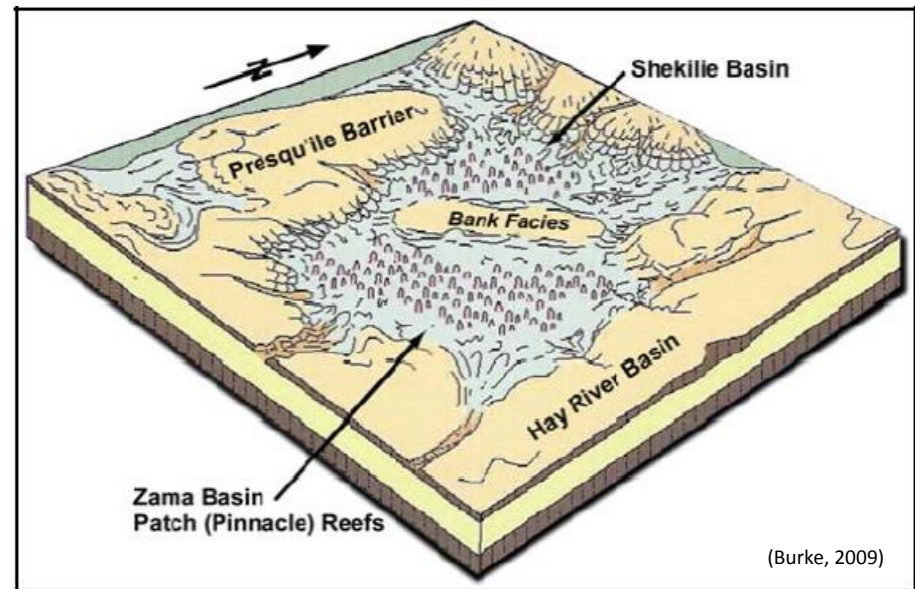
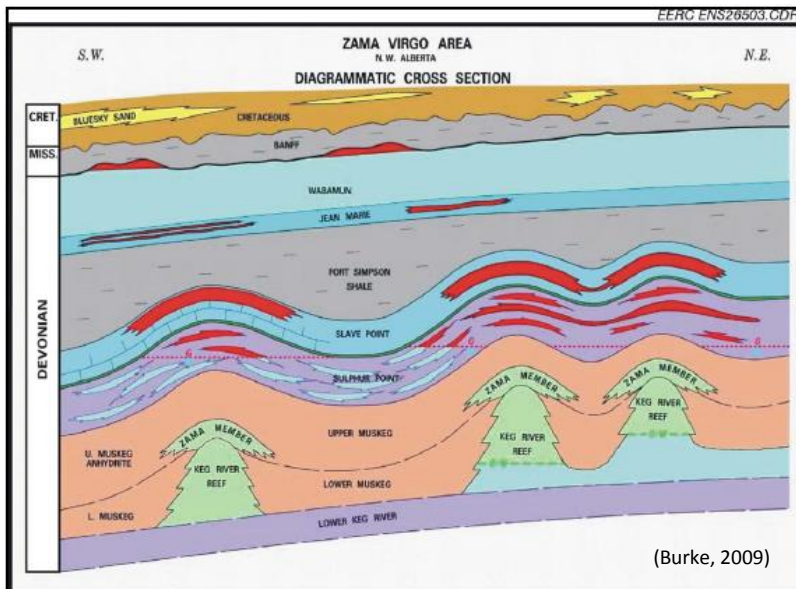
(Modified from Core Laboratories' Stratigraphic Correlation Chart: www.landman.ca/pdf/CORELAB.pdf)

Devonian Reef Overview: Keg River Formation



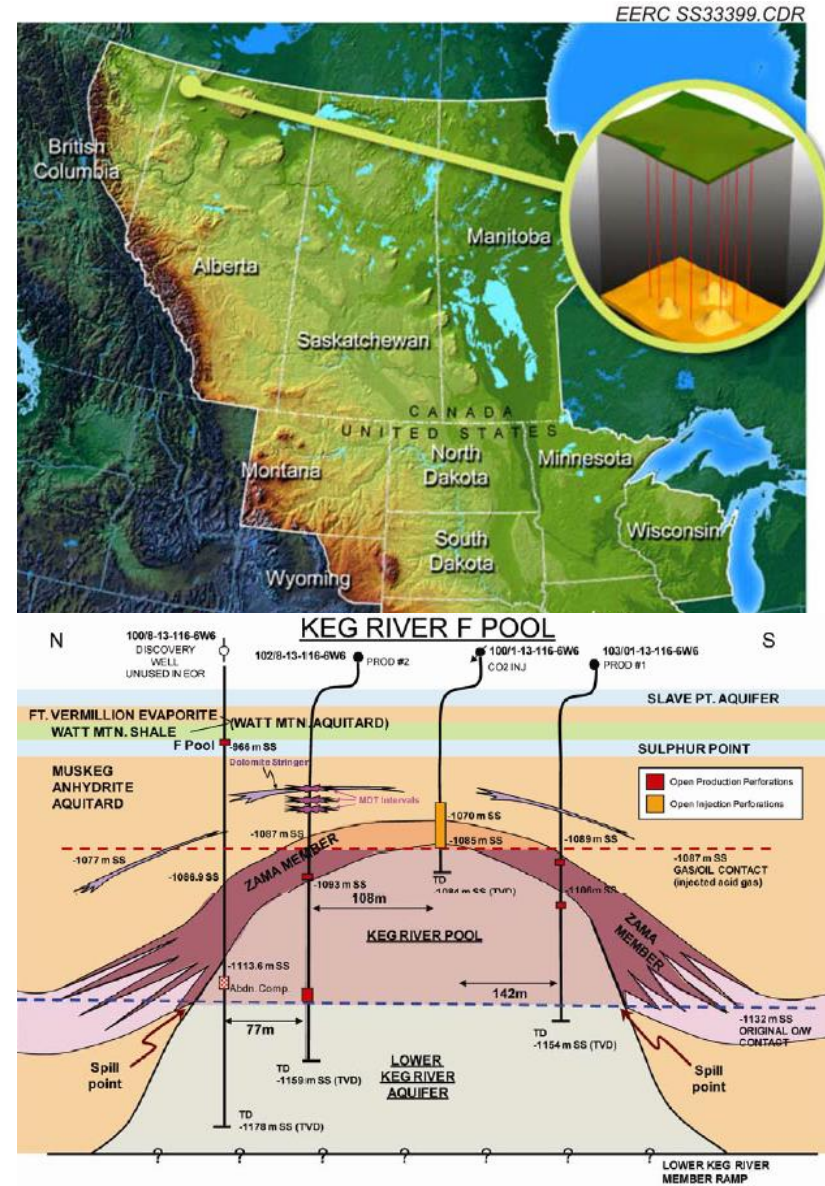
Zama Sub-basin Keg River Pinnacle Reefs

- Up to 400 ft in relief
- 40 acres (0.16 km²) at base
- Largely dolomitic
- Intergrain to microfracture porosity
- Encased in Muskeg anhydrite

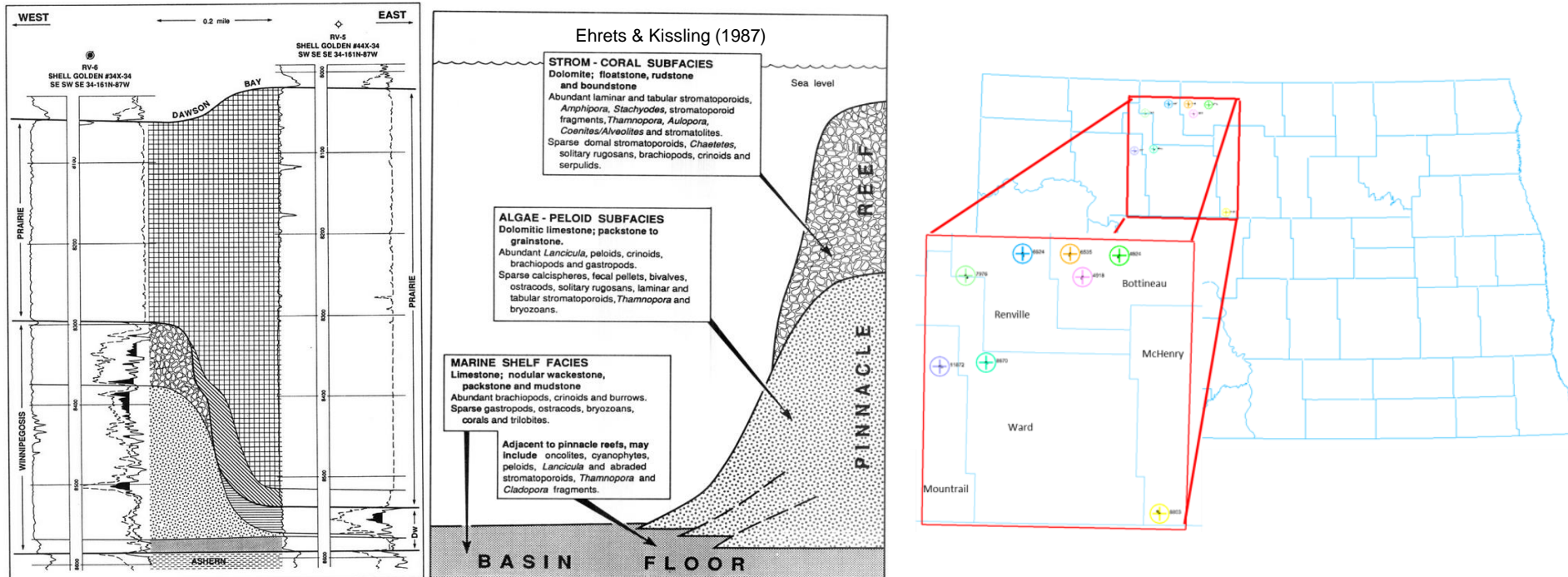


CO₂ EOR Case Study: Zama Oil Field, Northwestern Alberta

- PCOR Partnership Demonstration in cooperation with Apache Canada
- Acid gas (70% CO₂ + 30% H₂S) injection since December 2006
 - CO₂ EOR, CO₂ storage, and H₂S disposal
- Results through May 2012:
 - 121,200 metric tons of injected acid gas
 - 74,000 barrels of oil produced
 - Storage of approximately 36,600 metric tons of CO₂



Devonian Reef Overview: Winnipegosis Formation

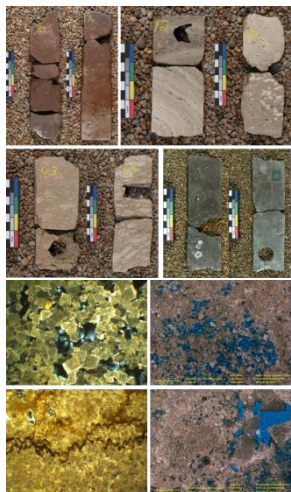


Williston Basin Winnipegosis Pinnacle Reefs

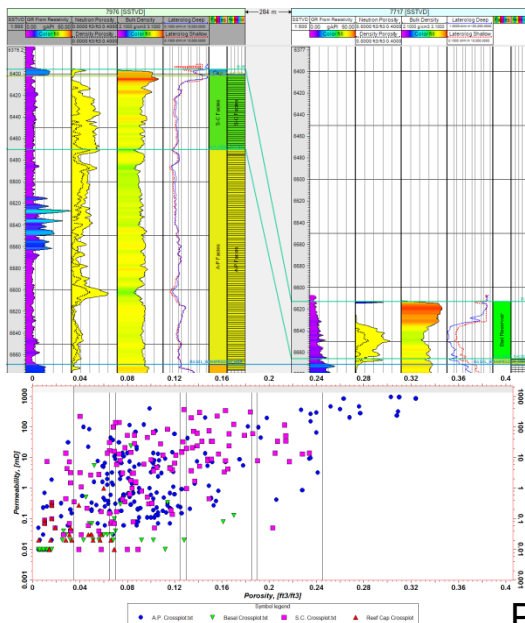
- Up to 350 ft in relief
- 0.3 to 3 miles base diameter
- Largely dolomitic
- Intergrain to vuggy porosity
- Encased in Prairie evaporites

Modeling Workflow

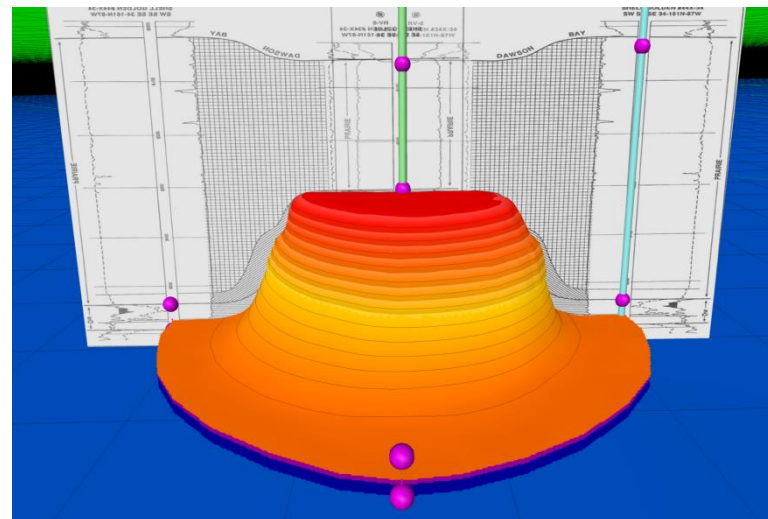
Characterization and Data Collection



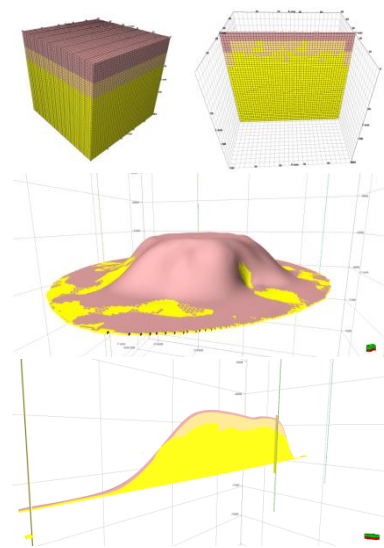
Well Log Correlation and Petrophysical Analysis



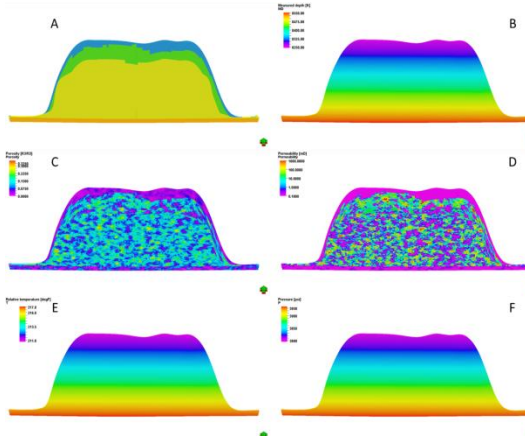
Structural Framework



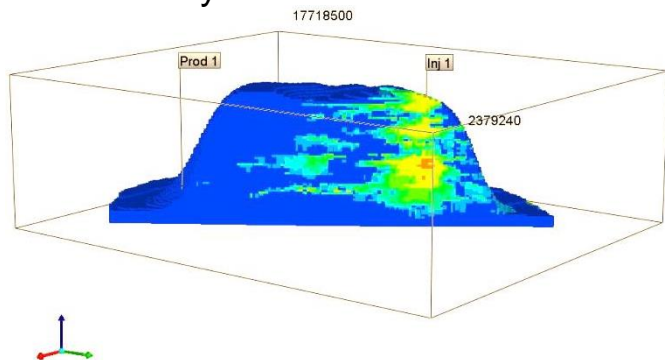
Facies Modeling



Property Modeling

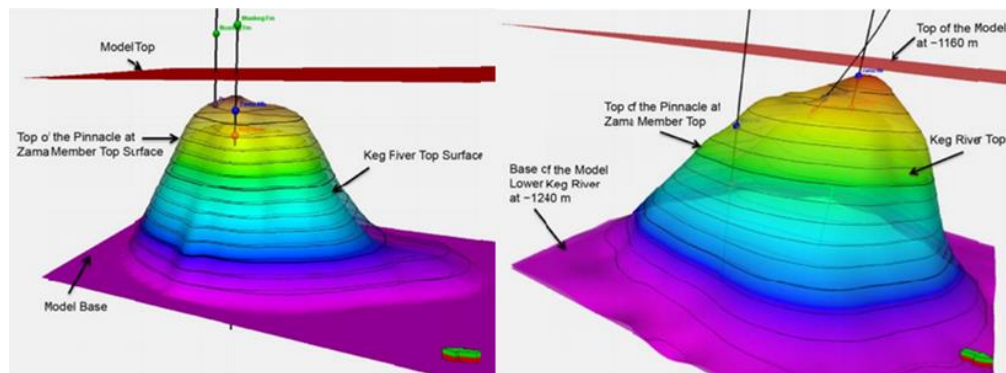


Dynamic Simulation

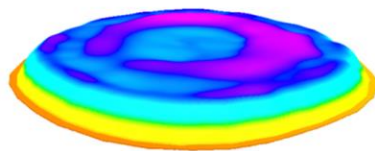


Structural Surface and Grid Development

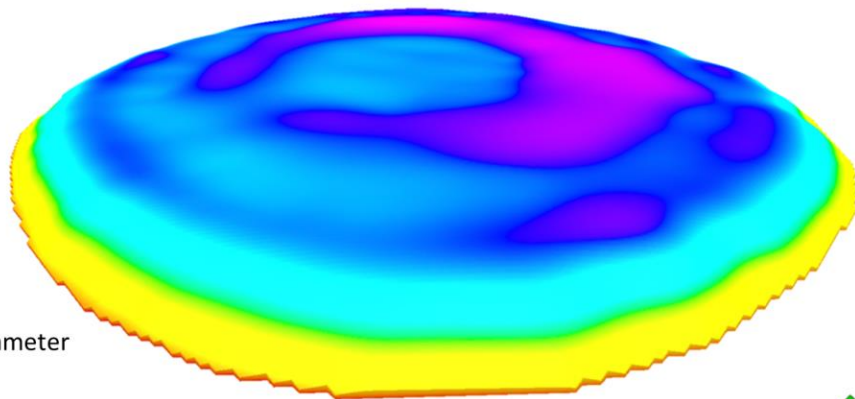
Seismic Data



0.3 mile base diameter

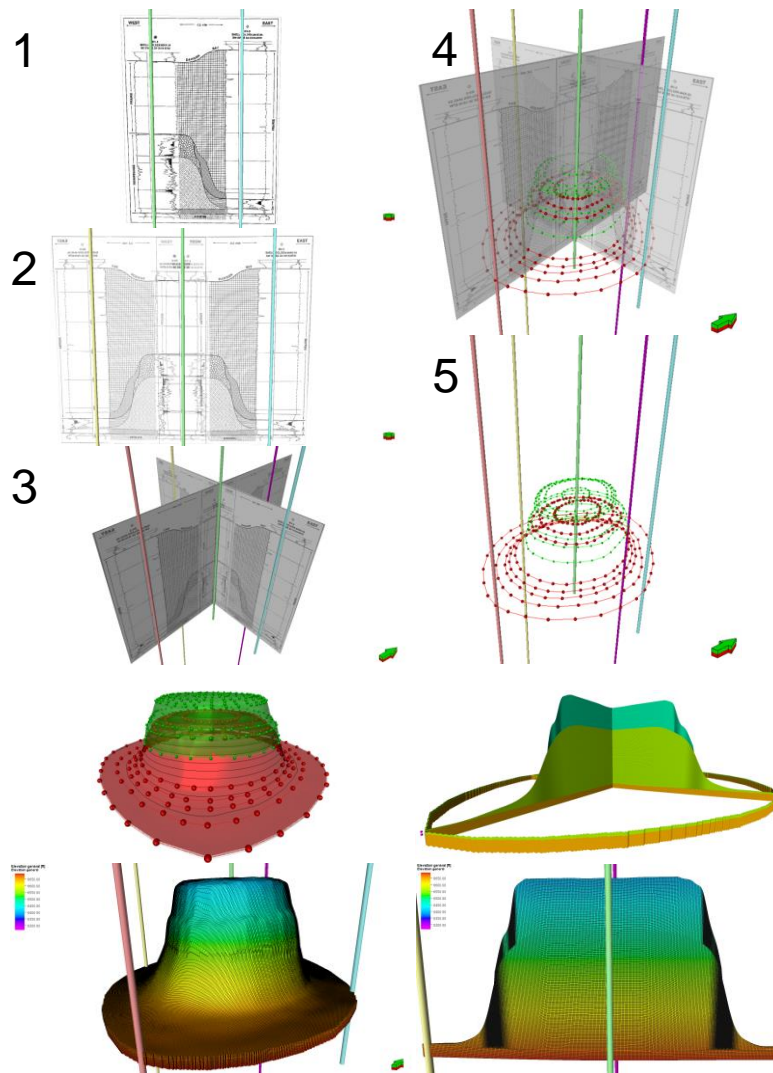


1.5 mile base diameter

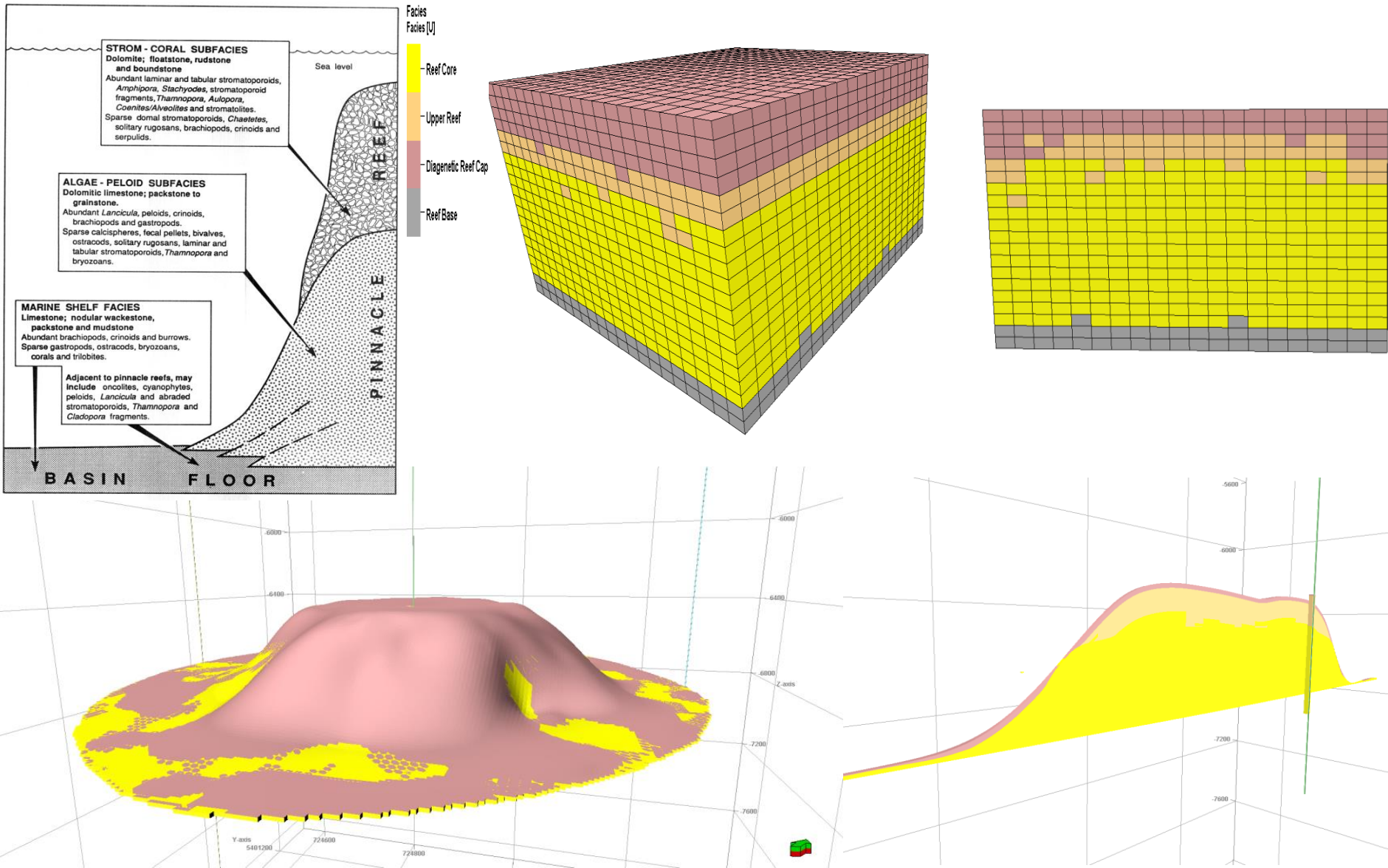


3 mile base diameter

Other Structural Definition

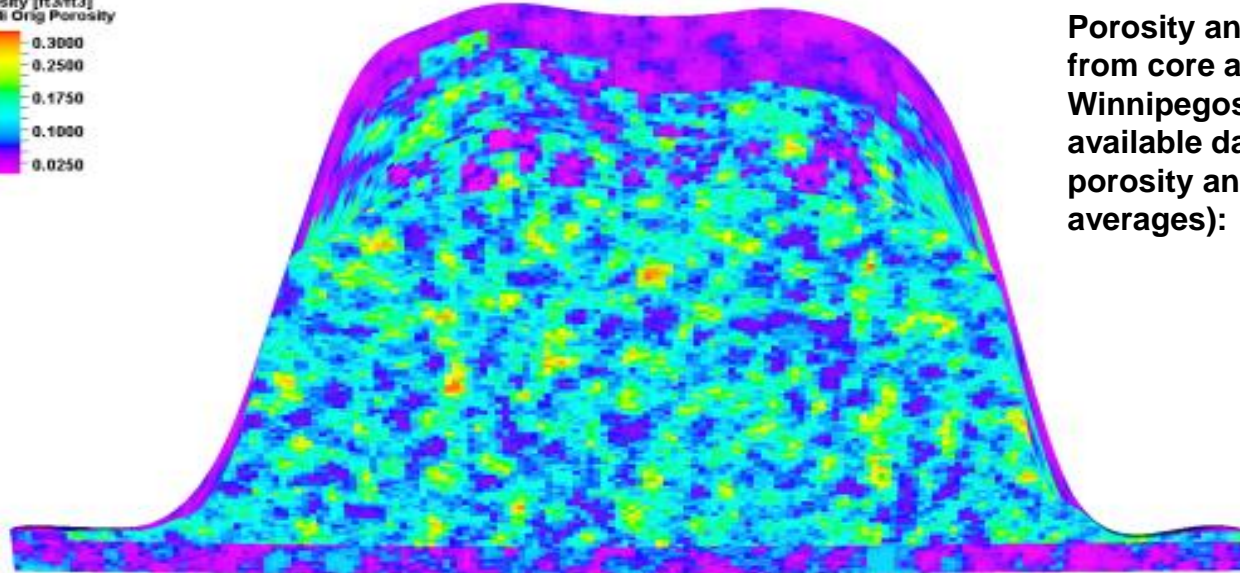
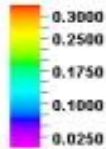


Winnipegosis: MPS Facies Modeling



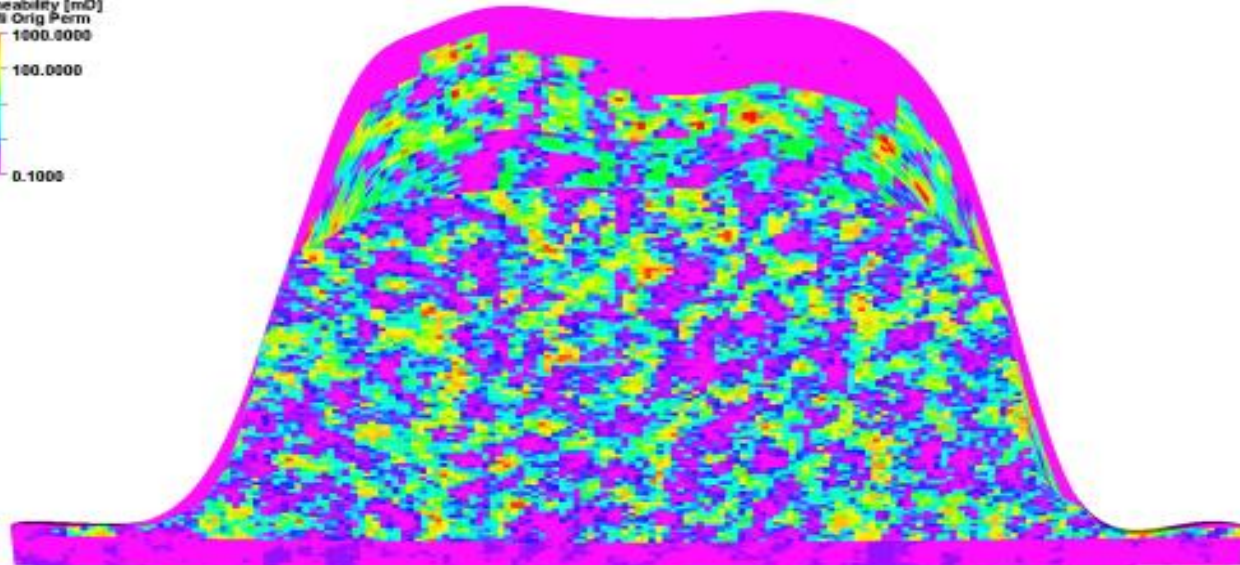
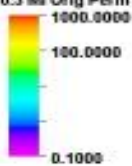
Petrophysical Property Modeling with Conditioning to Facies

Porosity [ft³/ft³]
0.3 Mi Orig Porosity



Porosity and permeability from core analysis for all Winnipegosis reef cores with available data (modeling porosity and permeability as averages):

Permeability [mD]
0.3 Mi Orig Perm



Static Storage Potential of Various Sized Reefs

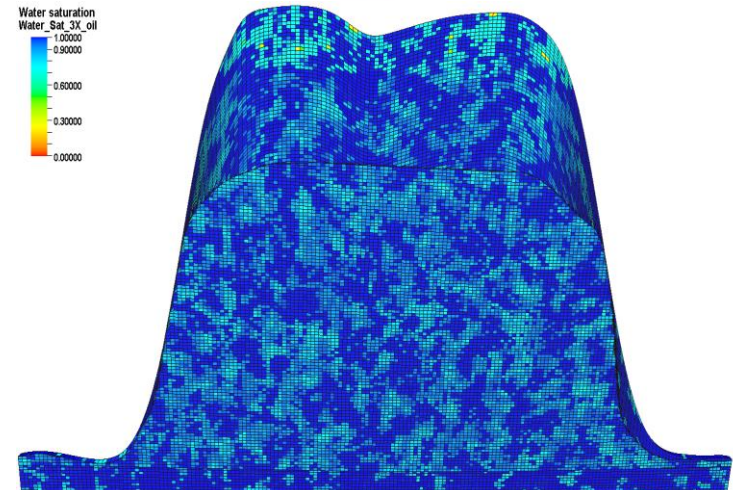
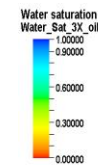
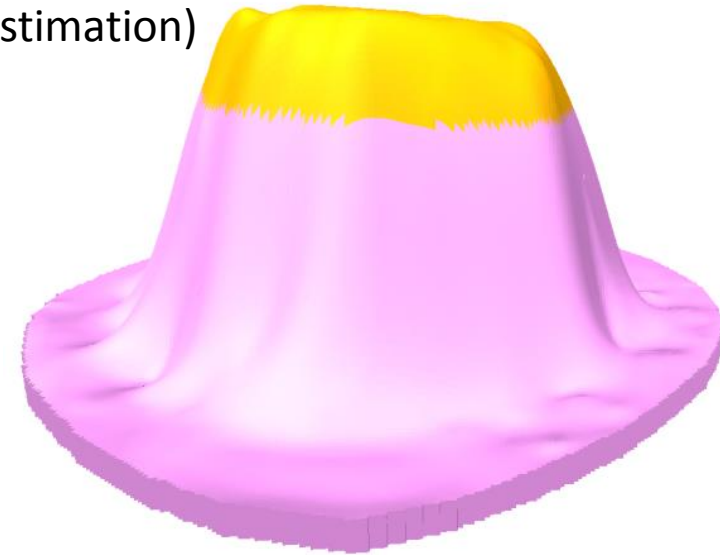
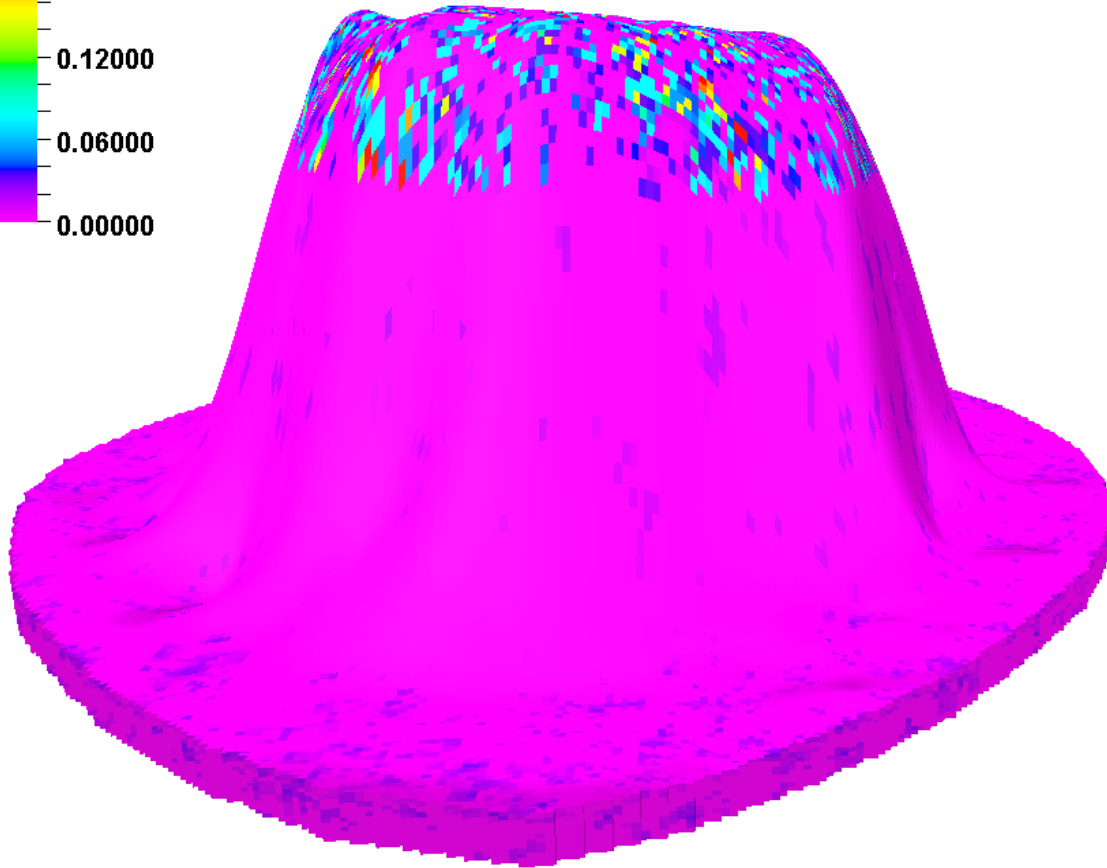
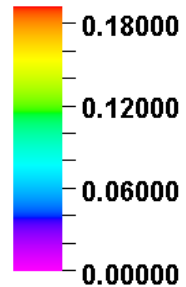
Static Storage Potential (assuming total formation fluid displacement):

Model Size	Net Volume (ft ³)	Pore Volume (ft ³)	CO ₂ Density (lb/ft ³)	Static Storage Potential (tons CO ₂)
0.3 Mile	392,902,594	42,054,576	38.15	802,191
1.5 Mile	16,226,536,038	1,617,963,868	38.15	30,862,661
3 Mile	68,358,862,682	6,802,061,062	38.15	129,749,315

Oil Saturation Modeling

Modeled from core **residual** oil saturations (likely an underestimation)

Oil saturation
Oil saturation



CO₂ EOR Recoverable Oil Estimates

(Calculated from core residual oil saturations; OIP is likely underestimated.)

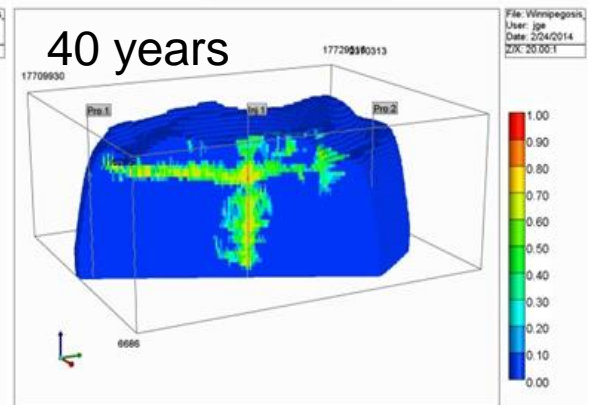
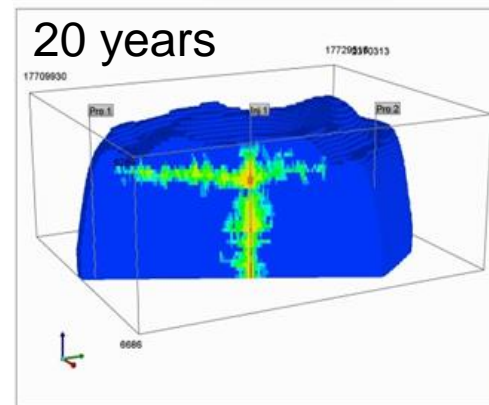
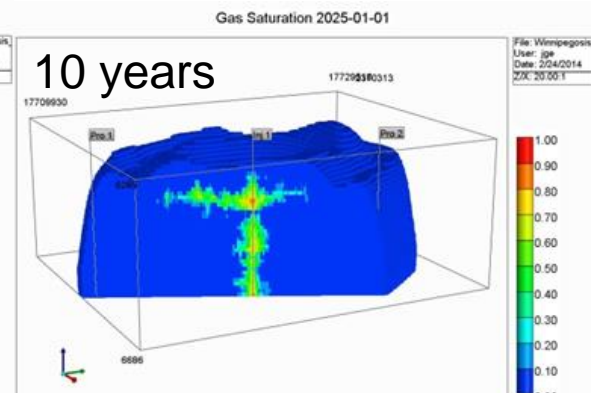
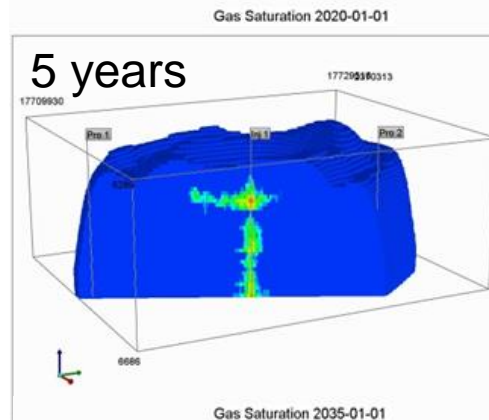
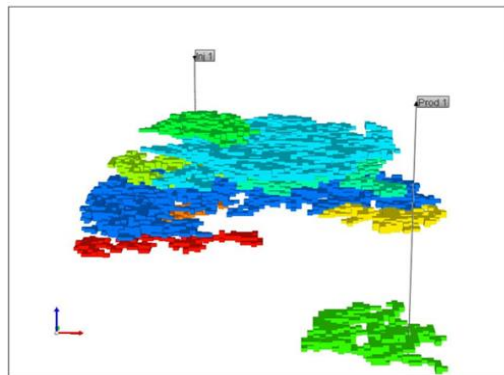
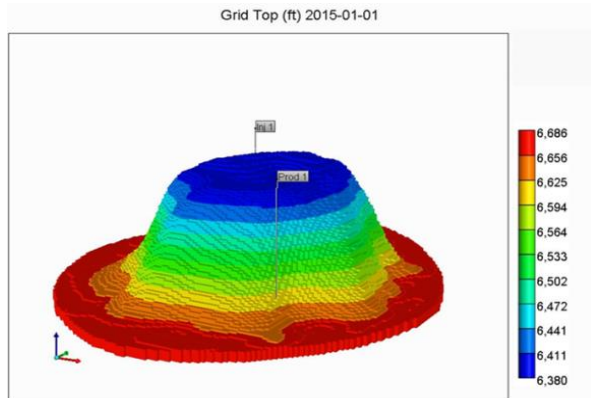
0.3-mile Pinnacle Reef				
HCPV (RB)	Shrinkage Factor	STOIIP (STB)	Recovery Factor	Total Recoverable Oil (STB)
54,573	1.2	45,478	5%	2274
54,573	1.2	45,478	10%	4548
54,573	1.2	45,478	15%	6822
1.5-mile Pinnacle Reef				
HCPV (RB)	Shrinkage Factor	STOIIP (STB)	Recovery Factor	Total Recoverable Oil (STB)
2,692,104	1.2	2,243,420	5%	112,171
2,692,104	1.2	2,243,420	10%	224,342
2,692,104	1.2	2,243,420	15%	336,513
3-mile Pinnacle Reef				
HCPV (RB)	Shrinkage Factor	STOIIP (STB)	Recovery Factor	Total Recoverable Oil (STB)
10,824,245	1.2	9,020,204	5%	451,010
10,824,245	1.2	9,020,204	10%	902,020
10,824,245	1.2	9,020,204	15%	1,353,031

*** These numbers are representative of hypothetical, average Winnipegosis pinnacle reefs differing on the basis of size.

Dynamic Simulation for CO₂ Injectivity Analysis

- Multiple cases were run considering different optimization parameters to achieve maximum injectivity.
 - Number of wells (injectors vs. producers)
 - Vertical vs. horizontal
 - Duration of injection

3 mile: gas saturation (one injector + two producers)



Dynamic Simulation for CO₂ Injectivity Analysis

- Preliminary results (selected):
 - 0.3-mile simulations: 5 years
 - 1.5-mile simulations: 10 years
 - 3-mile simulations: 20 years (except Case 5)
- More than 3 million tons of simulated injectivity in the 3-mile reef model with four operating wells over a span of 30 years, but...
 - Some economic considerations: drilling wells costs money, horizontal wells are more expensive than vertical wells, injecting over a longer time costs more money.
 - Injection efficiency: the most injected CO₂ with the fewest wells in the shortest amount of time.

Model Size	Case	Well Configuration	Total CO ₂ Injected, (ton)	Efficiency (Total Injected CO ₂ /Static Storage Potential), %
0.3 mile	Case 1	one injector + one producer	44,171	5.51
0.3 mile	Case 2	one injector + one producer	57,357	7.15
		horizontal perforation		
1.5 mile	Case 1	one injector + one producer	521,590	1.69
1.5 mile	Case 2	one injector + one producer	726,461	2.35
		horizontal perforation		
1.5 mile	Case 3	one injector + two producers	793,798	2.57
		horizontal perforation		
1.5 mile	Case 4	two injectors + two producers	875,415	2.84
3 mile	Case 1	one injector	340,682	0.26
3 mile	Case 2	one injector + one producer	1,030,370	0.79
3 mile	Case 3	one injector + one producer	1,516,140	1.17
		horizontal perforation		
3 mile	Case 4	one injector + two producers	1,924,970	1.48
		horizontal perforation		
3 mile	Case 5	two inj. + two prod., 30 yr	3,212,800	2.48

Discussion and Conclusion

- Geocellular modeling objectives:
 - Characterizing the pinnacle reef structures
 - Replicating the natural heterogeneity thought to be present in the reservoir
 - Increasing our knowledge of reef potential in the applications of CO₂ EOR and storage
- Modeled reefs are a product of averages
 - Variability is noted in pinnacle reef population

Discussion and Conclusion

- The 0.3-mile-diameter model shows limited feasibility for production or injection.
- Simulation cases with only one injector exhibit minimal injectivity.
- The 1.5-mile- and 3-mile-diameter model analyses show more promising results
 - CO₂ EOR recoverable reserves greater than 500,000 bbl possible
 - Potential geologic storage in excess of 1 million tons of CO₂.

Discussion and Conclusion

- Geologic storage of CO₂ is becoming a more popular idea.
 - Zama Field case study (NW Alberta) showing promising results.
 - “With over 700 pinnacle reef structures in the Zama subbasin, a careful selection of eight to sixteen pinnacle structures can provide a total storage capacity in excess of 10 MMt over the project span ranging from 4.5 years to 20 years” (Saini and others, 2013).
- Geologic CO₂ storage will be utilized more in the future and may prove to be an important tool for a “greener” and more sustainable existence.

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References

- Burke L. PCOR project Apache Zama F Pool acid gas EOR & CO₂ storage. Report prepared by RPS Energy Canada for the Energy & Environmental Research Center, 2009.
- Ehrets, J.R., and Kissling, D.L., 1987, Winnipegosis platform margin and pinnacle reef reservoirs, northwestern North Dakota, *in* Fischer, D.W., ed., Fifth International Williston Basin Symposium: North Dakota Geological Survey, Grand Forks, North Dakota, p. 131.
- Jin, J., Bergman, K.M., 2001. Revised Stratigraphy of the Middle Devonian (Givetian) Winnipegosis Carbonate-Prairie Evaporite Transition, Elk Point Group, Southern Saskatchewan. *Bulletin of Canadian Petroleum Geology*, Vol.49, No.4, P.441-457.
- Saini, D, Gorecki, C.D., Knudsen, D.J, Sorensen, J.A., Steadman, E.N., 2013, A simulation study of simultaneous acid gas EOR and CO₂ storage at Apache's Zama F Pool: Elsevier, *Energy Procedia*, v.37, p. 3891–3900.
- Smith, S.A., Sorensen, J.A., Steadman, E.N., Harju, J.A., Jackson, B., Nimchuk, D., Burke, L., 2010. Plains CO₂ Reduction (PCOR) Partnership (Phase II) –Zama Field Validation Test Regional Technology Implementation Plan, U.S. Department of Energy, National Energy Technology Laboratory, Morgantown, West Virginia.

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